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Heavy Flavour production as probe of Gluon Sivers Function

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Abstract Heavy flavour production like J/ψ and D- meson production in scattering of electrons/unpolarized protons off polarized proton target offer promising probes to investigate gluon Sivers function. In this talk, I will summarize our recent work on trasverse single spin asymmetry in J/ψ -production and D - meson production in pp^\uparrow scattering using a generalized parton model approach. We compare predictions obtained using different models of gluon Sivers function within this approach and then, taking into account the transverse momentum dependent evolution of the unpolarized parton distribution functions and gluon Sivers function, we study the effect of evolution on asymmetry.

Keywords Gluon Sivers Function · TMD evolution · SSA

1 Introduction

Gluon Sivers function (GSF) belongs to a class of transverse momentum dependent parton distribution functions, collectively called TMDs, which are needed to explain the transverse single spin asymmetries (TSSAs) that arise in the scattering of a transversely polarized nucleon off an unpolarized nucleon (or virtual photon) target and are due to orbital motion of quarks and gluons or due to recoil of gluons radiated off the active quarks. TSSA for inclusive process $A^\uparrow + B \rightarrow C + X$ is defined as

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \quad (1)$$

where $d\sigma^\uparrow$ and $d\sigma^\downarrow$ represent the cross section for scattering of a transversely polarized hadron A off an unpolarized hadron (or lepton) B with A being upwards (downwards) polarized with respect to the production

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plane. The magnitude of these asymmetries observed by HERMES and COMPASS collaborations [1; 2; 3] was found to be larger than perturbative QCD (pQCD) predictions based on conventional collinear factorization [4]. One of the two approaches to explain these large asymmetries is based on a generalized factorization formula called transverse momentum dependent (TMD) factorization, in which parton distribution functions (PDFs) of collinear factorization theorem are replaced by TMDs, which take into account the spin and intrinsic transverse momentum dependence of PDFs. Gluon Sivers Function (GSF) is one such TMD, which parametrizes the correlations between the azimuthal distribution of an unpolarized parton and the spin of its transversely polarized parent hadron [5; 6]:

$$\Delta^N f_{a/p^\uparrow}(x, k_\perp) \equiv \hat{f}_{a/p^\uparrow}(x, \mathbf{k}_\perp) - \hat{f}_{a/p^\downarrow}(x, \mathbf{k}_\perp) \quad (2)$$

Quark Sivers function have been studied extensively and their parameterizations have been extracted from SIDIS experimental data from HERMES, COMPASS and JLab experiments. However, not much information is available about GSF so far. Recently, the first rough estimates of GSF have been obtained by D'Alesio *et al* [7] by fitting to midrapidity data on $pp^\uparrow \rightarrow \pi^0 X$ taken by PHENIX collaboration at RHIC and, by using the quark Sivers parameters extracted earlier from SIDIS data. One now needs to identify processes for which predictions using these fits can be obtained and compared with data.

Heavy quark and quarkonium systems are natural probes to study the GSF as the production is sensitive to intrinsic transverse momentum especially at low momentum. SSAs in low virtuality electroproduction of J/ψ have been estimated by us using a generalization of color evaporation model of quarkonium production with TMDPDF's [8; 9; 10]. SSA in D Meson production in pp^\uparrow scattering, which can be used as a clean probe of Gluon Sivers Function [11] were calculated using a Generalized Parton Model approach with two extreme values of GSF - zero and maximum. It was shown that the gluon contribution dominates over quark contribution at RHIC energy and asymmetries up to 25 % were predicted with saturated GSF.

Recent measurement of asymmetry in J/ψ production at PHENIX experiment with polarized proton beam suggests the need for a phenomenological study of TSSA in heavy flavor production - both open and closed-as probes of GSF. Here, I summarize our recent work on transverse single spin asymmetry in the processes $pp^\uparrow \rightarrow J/\psi + X$ and $pp^\uparrow \rightarrow D + X$, where we have estimated TSSA using various parametrizations of GSF presently available and have also studied the effect of TMD evolution of Sivers function on TSSA.

In Section 2, we present different parameterizations of GSF that we have used. In Section 3, we have summarized our work in Ref [12] and in Section 3, we present our preliminary results for TSSA in $pp^\uparrow \rightarrow J/\psi + X$. Here, we also compare our estimates with the recent Phenix data. In Section 4, we present a summary of our results [13].

2 Gluon Sivers Function

The standard Gaussian form is used for the unpolarized TMD PDF

$$f_{i/p}(x, k_\perp; Q) = f_{i/p}(x, Q) \frac{1}{\pi \langle k_\perp^2 \rangle} e^{-k_\perp^2 / \langle k_\perp^2 \rangle} \quad (3)$$

with $\langle k_\perp^2 \rangle = 0.25 \text{ GeV}^2$ and $i = q, g$. For the Sivers function, we use the parametrization [7]

$$\Delta^N f_{i/p^\uparrow}(x, k_\perp; Q) = 2 \mathcal{N}_i(x) f_{i/p}(x, Q) h(k_\perp) \frac{e^{-k_\perp^2 / \langle k_\perp^2 \rangle}}{\pi \langle k_\perp^2 \rangle} \quad (4)$$

with

$$\mathcal{N}_i(x) = N_i x^{\alpha_i} (1-x)^{\beta_i} \frac{(\alpha_i + \beta_i)^{\alpha_i + \beta_i}}{\alpha_i^{\alpha_i} \beta_i^{\beta_i}}, \quad h(k_\perp) = \sqrt{2e} \frac{k_\perp}{M_1} e^{-k_\perp^2 / M_1^2} \quad (5)$$

and

$$h(k_\perp) \frac{e^{-k_\perp^2 / \langle k_\perp^2 \rangle}}{\pi \langle k_\perp^2 \rangle} = \frac{\sqrt{2e}}{\pi} \sqrt{\frac{1-\rho}{\rho}} k_\perp \frac{e^{-k_\perp^2 / \rho \langle k_\perp^2 \rangle}}{\langle k_\perp^2 \rangle^{3/2}}, \quad (6)$$

where N_i , α_i , β_i , M_1 and ρ are the best fit parameter.

We estimate asymmetries using the recently fitted GSF parameters given in Table 1. These fits have been

Table 1 SIDIS parameters for GSF and best fit parameters for u and d quark used in BV parametrization.

DMP-SIDIS 1	$N_g = 0.65$	$\alpha_g = 2.8$	$\beta_g = 2.8$	$\rho = 0.687$	$\langle k_\perp^2 \rangle = 0.25 \text{ GeV}^2$
DMP-SIDIS 2	$N_g = 0.05$	$\alpha_g = 0.8$	$\beta_g = 1.4$	$\rho = 0.576$	
u quark	$N_u = 0.4$	$\alpha_u = 0.35$	$\beta_u = 0.26$	$\langle k_\perp^2 \rangle = 0.25 \text{ GeV}^2$	$M_1^2 = 0.19$
d quark	$N_d = -0.97$	$\alpha_d = 0.44$	$\beta_d = 0.90$		

obtained by fitting $pp^\uparrow \rightarrow \pi^0 + X$ asymmetry data at RHIC [14]. We present estimates for SSA in D meson production and J/ψ production using these parameters, which we will call DMP fits following Ref. [12]. In case of J/ψ production, we also compare our predictions with those obtained using parameters we have used in our earlier work, which we call BV parameters as those were fitted using a model given by Boer and Vogelsang [15]. This parametrization is expressed as

$$\mathcal{N}_g(x) = \frac{\mathcal{N}_u + \mathcal{N}_d}{2} \quad (BV - a) \quad \text{and} \quad \mathcal{N}_g(x) = \mathcal{N}_d \quad (BV - b). \quad (7)$$

The difference between DMP-SIDIS1 and DMP-SIDIS2 parameters is that the former were fitted using a parametrization of quark Sivers function which took into account only u and d quark flavors while for the latter, s quark contribution was also included. The best fits parameter for up and down valance quark Sivers function we have used are given in Ref. [16]. We also study the effect of QCD evolution of TMD PDF's using the formalism of Ref. [17]. For this study we use the BV parameters only for both DGLAP and TMD evolution cases, since the DMP fits took into account DGLAP evolution only.

3 Transverse Single Spin Asymmetry in $pp^\uparrow \rightarrow DX$

We estimate SSA in D Meson production in pp^\uparrow scattering using the Generalized Parton Model approach. The numerator and denominator of asymmetry are given by [11],

$$\begin{aligned} \frac{E_D d\sigma^{p^\uparrow p \rightarrow DX}}{d^3 \mathbf{p}_D} - \frac{E_D d\sigma^{p^\downarrow p \rightarrow DX}}{d^3 \mathbf{p}_D} &= \int dx_a dx_b dz d^2 \mathbf{k}_{\perp a} d^2 \mathbf{k}_{\perp b} d^3 \mathbf{k}_D \delta(\mathbf{k}_D \cdot \hat{\mathbf{p}}_c) \delta(\hat{s} + \hat{t} + \hat{u} - 2m_c^2) \mathcal{C}(x_a, x_b, z, \mathbf{k}_D) \\ &\quad \left\{ \sum_q \left[\Delta^N f_{q/p^\uparrow}(x_a, \mathbf{k}_{\perp a}) f_{\bar{q}/p}(x_b, \mathbf{k}_{\perp b}) \frac{d\hat{\sigma}^{q\bar{q} \rightarrow c\bar{c}}}{d\hat{t}}(x_a, x_b, \mathbf{k}_{\perp a}, \mathbf{k}_{\perp b}, \mathbf{k}_D) D_{D/c}(z, \mathbf{k}_D) \right] \right. \\ &\quad \left. + \left[\Delta^N f_{g/p^\uparrow}(x_a, \mathbf{k}_{\perp a}) f_{g/p}(x_b, \mathbf{k}_{\perp b}) \frac{d\hat{\sigma}^{gg \rightarrow c\bar{c}}}{d\hat{t}}(x_a, x_b, \mathbf{k}_{\perp a}, \mathbf{k}_{\perp b}, \mathbf{k}_D) D_{D/c}(z, \mathbf{k}_D) \right] \right\} \\ \frac{E_D d\sigma^{p^\uparrow p \rightarrow DX}}{d^3 \mathbf{p}_D} + \frac{E_D d\sigma^{p^\downarrow p \rightarrow DX}}{d^3 \mathbf{p}_D} &= 2 \int dx_a dx_b dz d^2 \mathbf{k}_{\perp a} d^2 \mathbf{k}_{\perp b} d^3 \mathbf{k}_D \delta(\mathbf{k}_D \cdot \hat{\mathbf{p}}_c) \delta(\hat{s} + \hat{t} + \hat{u} - 2m_c^2) \mathcal{C}(x_a, x_b, z, \mathbf{k}_D) \\ &\quad \times \left\{ \sum_q \left[\hat{f}_{q/p}(x_a, \mathbf{k}_{\perp a}) \hat{f}_{\bar{q}/p}(x_b, \mathbf{k}_{\perp b}) \frac{d\hat{\sigma}^{q\bar{q} \rightarrow c\bar{c}}}{d\hat{t}}(x_a, x_b, \mathbf{k}_{\perp a}, \mathbf{k}_{\perp b}, \mathbf{k}_D) \hat{D}_{D/c}(z, \mathbf{k}_D) \right] \right. \\ &\quad \left. + \left[\hat{f}_{g/p}(x_a, \mathbf{k}_{\perp a}) \hat{f}_{g/p}(x_b, \mathbf{k}_{\perp b}) \frac{d\hat{\sigma}^{gg \rightarrow c\bar{c}}}{d\hat{t}}(x_a, x_b, \mathbf{k}_{\perp a}, \mathbf{k}_{\perp b}, \mathbf{k}_D) \hat{D}_{D/c}(z, \mathbf{k}_D) \right] \right\} \quad (8) \end{aligned}$$

respectively, where all the symbols have usual meaning [12].

We present our estimates of asymmetry in D meson production at $\sqrt{s} = 200 \text{ GeV}$ using DMP fits given in Table 1. Estimates of asymmetry at $\sqrt{s} = 115 \text{ GeV}$ and $\sqrt{s} = 500 \text{ GeV}$ can be found in Ref. [12]. In Figure 2, we have presented comparison of predictions using DGLAP evolved and TMD evolved GSF using BV parameters [15].

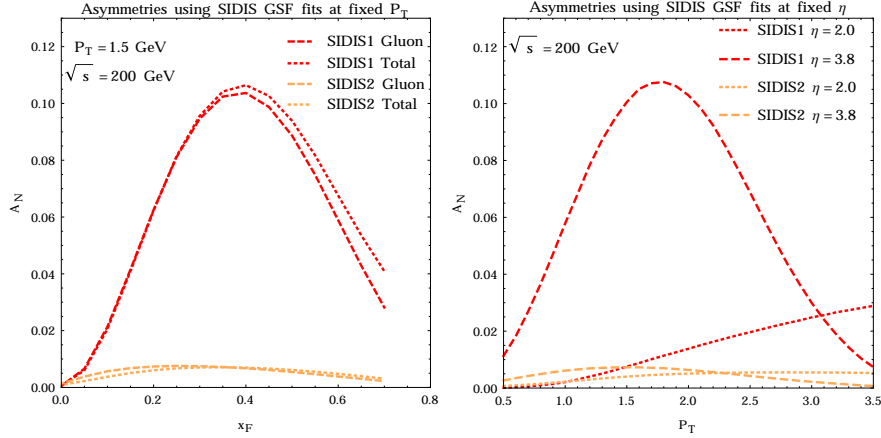


Fig. 1 Asymmetries in D meson production using DMP fits (a) x_F -distribution and (b) p_T -distribution using DMP SIDIS1 and DMP SIDIS 2 fits [12]

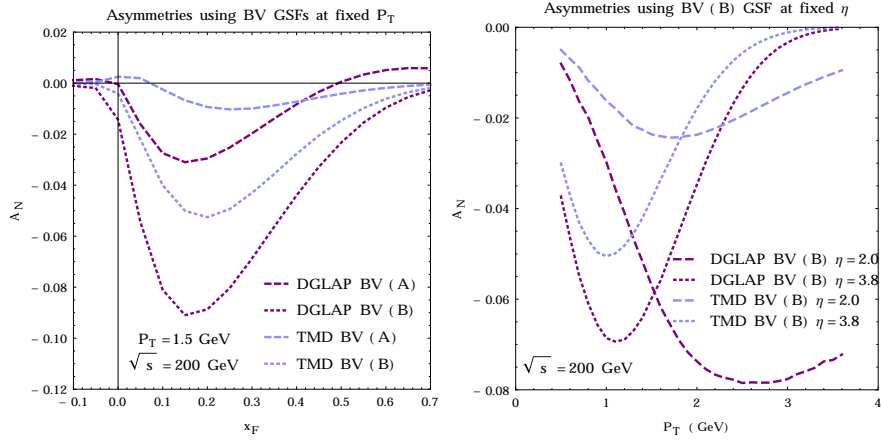


Fig. 2 Comparison of asymmetries in D meson production using BV parameters for GSF fitted using DGLAP evolution and TMD evolution (a) x_F -distribution and (b) p_T -distribution [12]

4 Transverse Single Spin Asymmetry in $pp^\uparrow \rightarrow J/\psi X$

In this section, we present our estimates of TSSA in the process $p + p^\uparrow \rightarrow J/\psi + X$ obtained using a generalized parton model approach and the color evaporation model (CEM) of J/ψ production [13]:

$$\sigma^{p+p \rightarrow J/\psi+X} = F_{J/\psi} \int_{4m_c^2}^{4m_D^2} dM_{c\bar{c}}^2 \int dx_a d^2k_{\perp a} dx_b d^2k_{\perp b} f_{g/p^\uparrow}(x_a, k_{\perp a}) f_{g/p}(x_b, k_{\perp b}) \frac{d\hat{\sigma}^{gg \rightarrow c\bar{c}}}{dM_{c\bar{c}}^2} \quad (9)$$

In this generalization of CEM, the numerator of the asymmetry in $p + p^\uparrow \rightarrow J/\psi + X$ is parameterized in terms of the Sivers function

$$\frac{d^4\sigma^\uparrow}{dydM^2d^2\mathbf{q}_T} - \frac{d^4\sigma^\downarrow}{dydM^2d^2\mathbf{q}_T} = \frac{1}{s} \int [d^2\mathbf{k}_{\perp a} d^2\mathbf{k}_{\perp b}] \Delta^N f_{g/p^\uparrow}(x_a, \mathbf{k}_{\perp a}) f_{g/p}(x_b, \mathbf{k}_{\perp b}) \delta^2(\mathbf{k}_{\perp a} + \mathbf{k}_{\perp b} - \mathbf{q}_T) \hat{\sigma}_0^{gg \rightarrow c\bar{c}}(M^2) \quad (10)$$

The denominator of the asymmetry is

$$\frac{d^4\sigma^\uparrow}{dydM^2d^2\mathbf{q}_T} + \frac{d^4\sigma^\downarrow}{dydM^2d^2\mathbf{q}_T} = \frac{2}{s} \int [d^2\mathbf{k}_{\perp a} d^2\mathbf{k}_{\perp b}] \left[f_{g/p}(x_a, \mathbf{k}_{\perp a}) f_{g/p}(x_b, \mathbf{k}_{\perp b}) \delta^2(\mathbf{k}_{\perp a} + \mathbf{k}_{\perp b} - \mathbf{q}_T) \hat{\sigma}_0^{gg \rightarrow c\bar{c}}(M^2) + f_{q/p}(x_a, \mathbf{k}_{\perp a}) f_{\bar{q}/p}(x_b, \mathbf{k}_{\perp b}) \delta^2(\mathbf{k}_{\perp a} + \mathbf{k}_{\perp b} - \mathbf{q}_T) \hat{\sigma}_0^{q\bar{q} \rightarrow c\bar{c}}(M^2) \right] \quad (11)$$

where, in Eq.(10), we have neglected the contribution of $q\bar{q}$ subprocess as it is negligible compared to gg subprocess. In Figure 3, we present our estimates of asymmetries calculated using the DMP SIDIS1 and SIDIS2 fits at $\sqrt{s} = 200$ GeV. Estimates of asymmetry at $\sqrt{s} = 115$ GeV and 500 GeV can be found in Ref. [13]. To investigate the effect of TMD evolution on asymmetry, we have also calculated asymmetries using BV parameters and the best fit parameters of the quark Sivers function (used in our earlier work on SSA in $e + p^\uparrow \rightarrow J/\psi + X$ and $p + p^\uparrow \rightarrow D + X$). In Figure 4, we compare the predictions with BV parameters obtained using DGLAP evolved and TMD evolved Sivers functions to assess the effect of TMD evolution on asymmetries. We compare our estimates with the PHENIX data [14] in figure 5. We have given estimates in three rapidity regions to compare with PHENIX experimental data. The backward and forward rapidity regions corresponding to ranges $-2.2 \leq y \leq -1.2$ and $2.2 \leq y \leq 1.2$ respectively and the mid rapidity region corresponding to range $-0.35 \leq y \leq 0.35$.

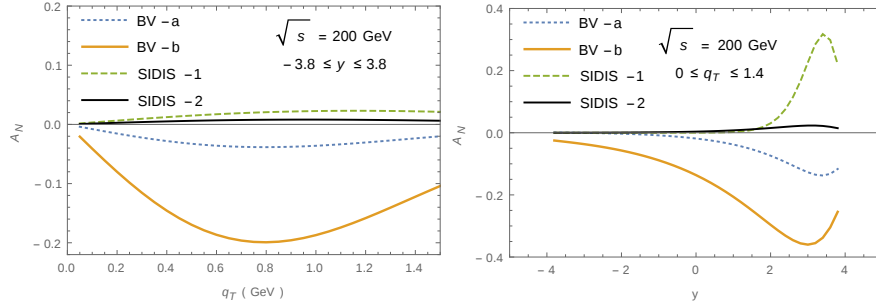


Fig. 3 Predictions of asymmetry in $p^\uparrow + p \rightarrow J/\psi + X$ at PHENIX ($\sqrt{s} = 200$ GeV). q_T and y integration ranges are $0 < q_T < 1.4$ GeV and $-3.8 < y < 3.8$ respectively. Left panel and right panel are plots of q_T and y distribution of asymmetry respectively [13].

5 Summary

We have presented estimates of TSSA in D Meson production and J/ψ production in pp^\uparrow scattering at $\sqrt{s} = 200$ GeV. In case of D-Meson production, symmetries are found to be substantial (up to 10%), while in case of J/ψ production, asymmetries are found to be consistent with the almost zero result of PHENIX experiment. In both cases, the contribution of gluon Sivers function is found to dominate over the quark contribution and the effect of TMD evolution is found to be reduction in the asymmetry estimates. Our comparison of estimated asymmetry with PHENIX data shows that asymmetry with SIDIS-2 and SIDIS-1 parameter set is within the experimental uncertainties of PHENIX data. We have also verified that results obtained using BV-a parameterization is well within experimental uncertainties of PHENIX data, while the estimates of asymmetry with BV-b is not in agreement with PHENIX data [13]. However, after taking into account TMD evolution, both the parameter sets lead to asymmetries that agree with near zero result of experiment.

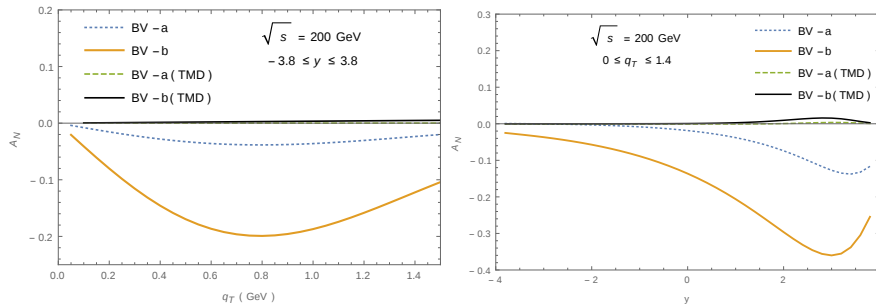


Fig. 4 Predictions of asymmetry with DGLAP and TMD evolution in $p^\uparrow + p \rightarrow J/\psi + X$ at $\sqrt{s} = 200$ GeV. q_T and y integration ranges are $0 < q_T < 1.4$ GeV and $-3.8 < y < 3.8$. Left panel and right panel are plots of q_T and y distribution of asymmetry respectively [13]

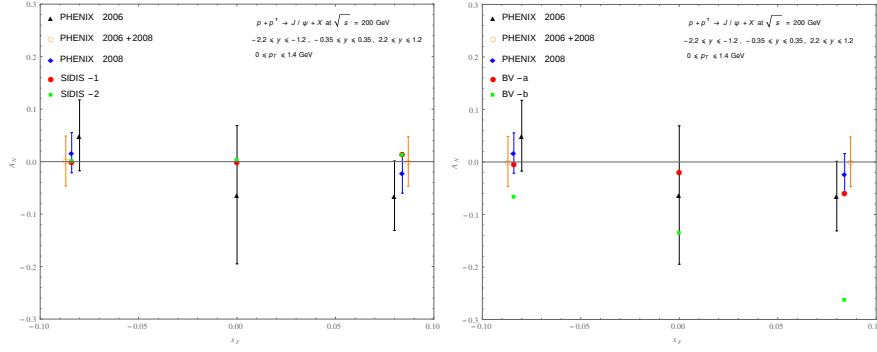


Fig. 5 Plots of asymmetry in $p^\dagger + p \rightarrow J/\psi + X$ at PHENIX experiment ($\sqrt{s} = 200$ GeV). Region of q_T integration is $0 < q_T < 1.4$ GeV. Asymmetry is in backward ($-2.2 < y < -1.2$), mid ($-0.35 < y < 0.35$) and forward ($1.2 < y < 2.2$) rapidity regions. In left panel we have compared asymmetry obtained using SIDIS-2 and SIDIS-1 parameters with PHENIX data. In right panel we have compared asymmetry obtained using BV-a and BV-b parametrization with TMD evolution with PHENIX data [13]

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References

1. A. Airapetian et al. Observation of a single spin azimuthal asymmetry in semiinclusive pion electro production. *Phys. Rev. Lett.*, 84:4047–4051, 2000.
2. A. Airapetian et al. Single spin azimuthal asymmetries in electroproduction of neutral pions in semiinclusive deep inelastic scattering. *Phys. Rev.*, D64:097101, 2001.
3. V. Yu. Alexakhin et al. First measurement of the transverse spin asymmetries of the deuteron in semi-inclusive deep inelastic scattering. *Phys. Rev. Lett.*, 94:202002, 2005.
4. U. D’Alesio and F. Murgia. Azimuthal and Single Spin Asymmetries in Hard Scattering Processes. *Prog. Part. Nucl. Phys.*, 61:394–454, 2008.
5. Dennis W. Sivers. Single Spin Production Asymmetries from the Hard Scattering of Point-Like Constituents. *Phys. Rev.*, D41:83, 1990.
6. Dennis W. Sivers. Hard scattering scaling laws for single spin production asymmetries. *Phys. Rev.*, D43:261–263, 1991.
7. U. D’Alesio, F. Murgia, and C. Pisano. Towards a first estimate of the gluon Sivers function from A_N data in pp collisions at RHIC. *JHEP*, 09:119, 2015.
8. Rohini M. Godbole, Anuradha Misra, Asmita Mukherjee, and Vaibhav S. Rawoot. Sivers Effect and Transverse Single Spin Asymmetry in $e + p^\dagger \rightarrow e + J/\psi + X$. *Phys. Rev.*, D85:094013, 2012.
9. Rohini M. Godbole, Anuradha Misra, Asmita Mukherjee, and Vaibhav S. Rawoot. Transverse Single Spin Asymmetry in $e + p^\dagger \rightarrow e + J/\psi + X$ and Transverse Momentum Dependent Evolution of the Sivers Function. *Phys. Rev.*, D88(1):014029, 2013.
10. Rohini M. Godbole, Abhiram Kaushik, Anuradha Misra, and Vaibhav S. Rawoot. Transverse single spin asymmetry in $e + p^\dagger \rightarrow e + J/\psi + X$ and Q^2 evolution of Sivers function-II. *Phys. Rev.*, D91(1):014005, 2015.
11. M. Anselmino, M. Boglione, U. D’Alesio, E. Leader, and F. Murgia. Accessing Sivers gluon distribution via transverse single spin asymmetries in p(transv. polarized) $p \rightarrow D X$ processes at RHIC. *Phys. Rev.*, D70:074025, 2004.
12. Rohini M. Godbole, Abhiram Kaushik, and Anuradha Misra. Transverse Single Spin Asymmetry in $p + p^\dagger \rightarrow D + X$. *To appear in Phys. Rev. D*, 2016.
13. Rohini M. Godbole, Abhiram Kaushik, Anuradha Misra, Vaibhav Rawoot, and Bipin Sonawane. Transverse Single Spin Asymmetry in $p + p^\dagger \rightarrow J/\psi + X$. *In progress*, 2016.
14. A. Adare et al. Measurement of transverse-single-spin asymmetries for midrapidity and forward-rapidity production of hadrons in polarized p+p collisions at $\sqrt{s}=200$ and 62.4 GeV. *Phys. Rev.*, D90(1):012006, 2014.
15. Daniel Boer and Werner Vogelsang. Asymmetric jet correlations in p p uparrow scattering. *Phys. Rev.*, D69:094025, 2004.
16. M. Anselmino, M. Boglione, U. D’Alesio, S. Melis, F. Murgia, and A. Prokudin. Sivers Distribution Functions and the Latest SIDIS Data. In *19th International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS 2011) Newport News, Virginia, April 11-15, 2011*, 2011.
17. John C. Collins, Davison E. Soper, and George F. Sterman. Transverse Momentum Distribution in Drell-Yan Pair and W and Z Boson Production. *Nucl. Phys.*, B250:199–224, 1985.